DEVIATIONS FROM DESIGN IMPACT PERFORMANCE OF AN AGGREGATE PIER SUPPORTED EMBANKMENT

Jay L. Hodkinson , GZA GeoEnvironmental, Inc., Manchester, NH, USA
James R. Wheeler, Design/Build Geotechnical, LLC, Marlborough, MA, USA
Christopher C. Benda, Vermont Agency of Transportation, Montpelier, VT, USA

Replacement of an aging twin span river crossing in Vermont required a temporary bridge to accommodate traffic during construction. Soils beneath the temporary approach embankment consisted of very soft organic clayey silt underlain by interbedded, loose alluvial fine sand and silt/clayey silt. Reinforcement was required for the southern temporary approach embankment to limit settlement and to increase global stability factors of safety. A ground improvement design was developed using Rammed Aggregate Pier® reinforcement and was included in the contract documents as an FHWA Category II Experimental Feature. Instrumentation intended to document the performance of the supported embankment was installed. Piers were then constructed and monitoring commenced as embankment and bridge construction occurred. Weekly instrumentation data reports indicated continuing excess pore water pressure, settlement, and lateral deformation of the subgrade soils as the embankment and temporary bridge abutment was constructed. In response to the unanticipated monitoring results, further investigation indicated that significant deviations from the conditions and basis upon which the ground support design was developed were made during construction. This paper discusses these deviations and their specific impacts to embankment support performance, how these deviations occurred, the role that the ground support system played in maintaining global stability, measures taken to limit further detrimental impacts to the embankment, and provides recommendations for contract document preparation and construction oversight to prevent similar situations from occurring on future projects.

Introduction

The project consisted of replacing Bridge No. 9 located on Vermont Route 125 in the western portion of Cornwall, Vermont, see Figure 1.

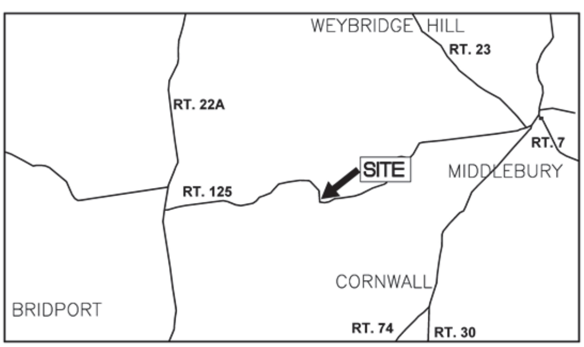


Figure 1 - Locus

The bridge spanned the Lemon Fair River, which meanders through rural bottomland to the east before ultimately joining Lake Champlain. The bridge was constructed in 1936 as a narrow, 2-span, 2-lane structure without sidewalks. The bridge was supported by two skeleton-type abutments and a solid wall pier. The abutments and pier were supported by a deep foundation system consisting of timber piles.

Historic plans indicate the approach embankments, constructed in 1936, doubled the width of previously placed approach embankments and generally consisted of miscellaneous fill and blast rock fill.

The replacement bridge was designed as a single span integral abutment structure to be constructed along the existing bridge alignment. A temporary detour bridge was to be constructed west of the mainline alignment to divert traffic during construction as shown in Figure 2. To accommodate the temporary bridge alignment, the mainline approach embankments were to be widened with grade raises up to 10 ft (3 m) proposed for the north and south approach embankments, respectively. In addition, the detour approach embankments were to be constructed adjacent to the existing embankments and partially "piggy backed" the existing embankments with grade raises of up to 16 ft (4.9 m) were proposed for the north and south detour approach embankments.

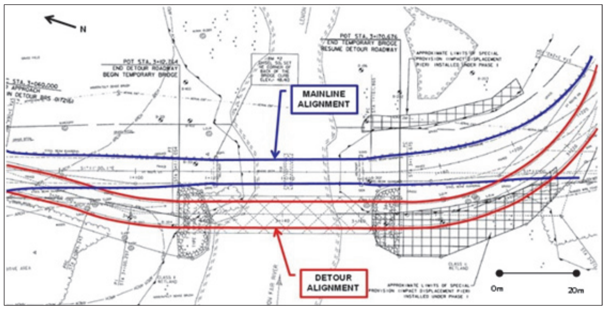


Figure 2 – Site Plan

Subsurface Conditions

The subsurface conditions encountered at the site varied significantly between the north and south side of the Lemon Fair River.

For the north abutments, the subsurface profile generally consisted of clay with organic soils underlain by clay, silty sand, and sand. The clay in was generally normal to over consolidated. Bedrock was not encountered to the maximum explored depth of 132 ft (40.2 m).

At the south abutments, subsurface conditions consisted generally of fill or organic soils underlain by silty clay or alternating silt and sand layers. Fill material encountered included an upper clay fill assumed to have been placed during the widening of the embankment in 1936 and a lower granular fill that was likely placed during the construction of the original embankment. The organic soils were highly compressible with a high organic content ranging from 22.5% to 35%. The underlying clay stratum had intermittent sand seams and a plasticity index of 25. A sand and silt stratum consisting of alternating layers of silty sand and silt was encountered below the organic or clay stratum. A cross section of the south embankment section is shown in Figure 3.

Groundwater was observed at a depth of 1.5 ft (0.5 m) and artesian conditions were encountered during drilling at 60 ft (18.3 m) below ground surface. Bedrock was not encountered to the maximum explored depth of 155 ft (47.2 m).

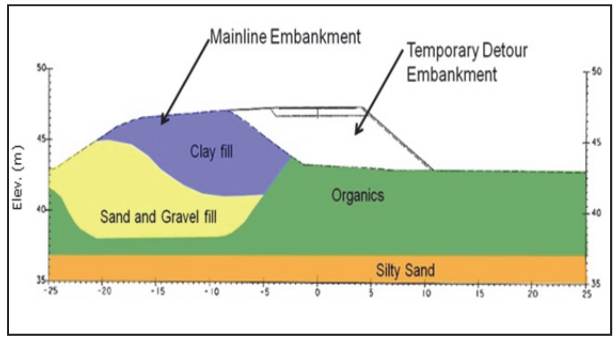


Figure 3 – South Detour Approach Abutment

Project Challenges

Project challenges differed between the north and south temporary bridge approach embankments. Due to the presence of compressible materials the initial design evaluations determined that the temporary bridge would be pile supported. In addition, the approach embankments would require ground improvement to limit total and differential settlement and provide additional strength to improve global stability.

The geotechnical challenge at the north approach embankment was the presence of normal to overconsolidated cohesive soils that were likely to cause total and differential settlement issues. In addition, archeological restrictions were placed on the north embankment area due to the recent discovery of an ancient Native American settlement. As a result of this discovery, archeological restrictions prohibited penetration of the ground surface during construction of the north temporary bridge abutment and embankment.

A soft organic deposit encountered at ground surface within the footprint of the south temporary detour embankment presented challenges associated with excessive settlement and global stability in addition to differential settlement issues associated with the proposed mainline widening.

Geotechnical Design Basis

To address the numerous geotechnical challenges, multiple ground improvement techniques were recommended. These recommendations were based on the assumption that the temporary detour bridge would be supported on a deep foundation system. Therefore, abutment loads were not included when the approach embankments were evaluated for settlement and global stability. Geotechnical recommendations were also based on the assumption that the detour approach embankments would be constructed of compacted granular fill with an equivalent friction angle of 34 degrees.

To address the global stability and settlement concerns at the south abutment, multiple ground improvement techniques were incorporated including wick drains and Rammed Aggregate Pier® (RAP) reinforcement. The wick drains were used to accelerate consolidation settlement rate and limit post construction settlement for the mainline. The RAPs were used to reduce post construction settlement and increase soil shear strength for global stability at the temporary approach embankment.

At the north approach embankment, wick drains were initially recommended to accelerate consolidation related settlement. However, as a result of the archeological restrictions placed on the project, wick drains were later omitted from the north abutment. Archeological restrictions also dictated that the temporary bridge abutment be supported on a shallow foundation system bearing in the approach embankment. The geotechnical consultant performed stability and settlement analyses for the north approach embankment to develop a preliminary design which consisted of a reinforced slope utilizing geogrids.

However, after numerous discussions, the project team decided that for this temporary construction, the contractor would be responsible for the final design of the bridge and approach embankments in accordance with Agency standard specifications. This decision was made with the understanding that the contractor would have to provide a design submittal to demonstrate that the proposed bridge and embankment design satisfied project performance criteria.

Project Timeline

The following timelines shown on Table 1 and Table 2 summarize key events beginning in the Fall of 2000, through final design and bridge construction. The timeline is important in understanding the decisions that were made to develop the final design as well as the decisions and made during construction.

Table 1 – Preconstruction Timeline

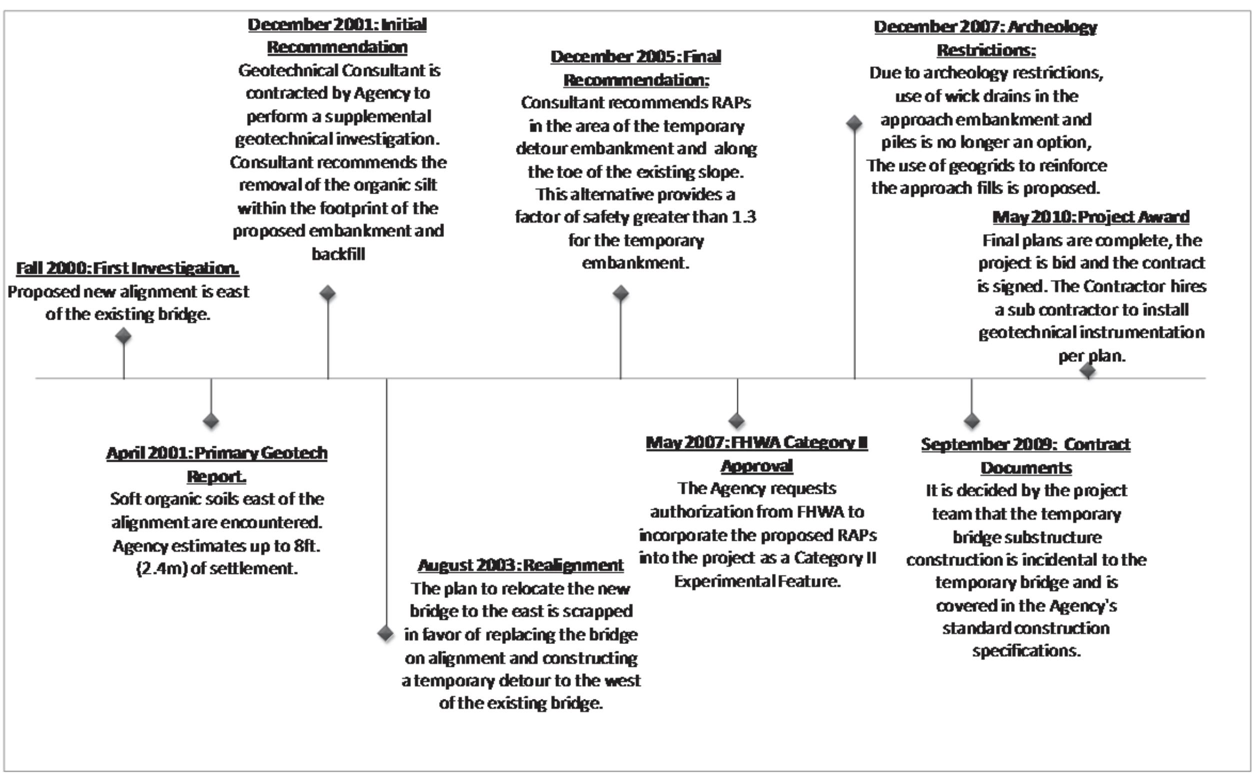
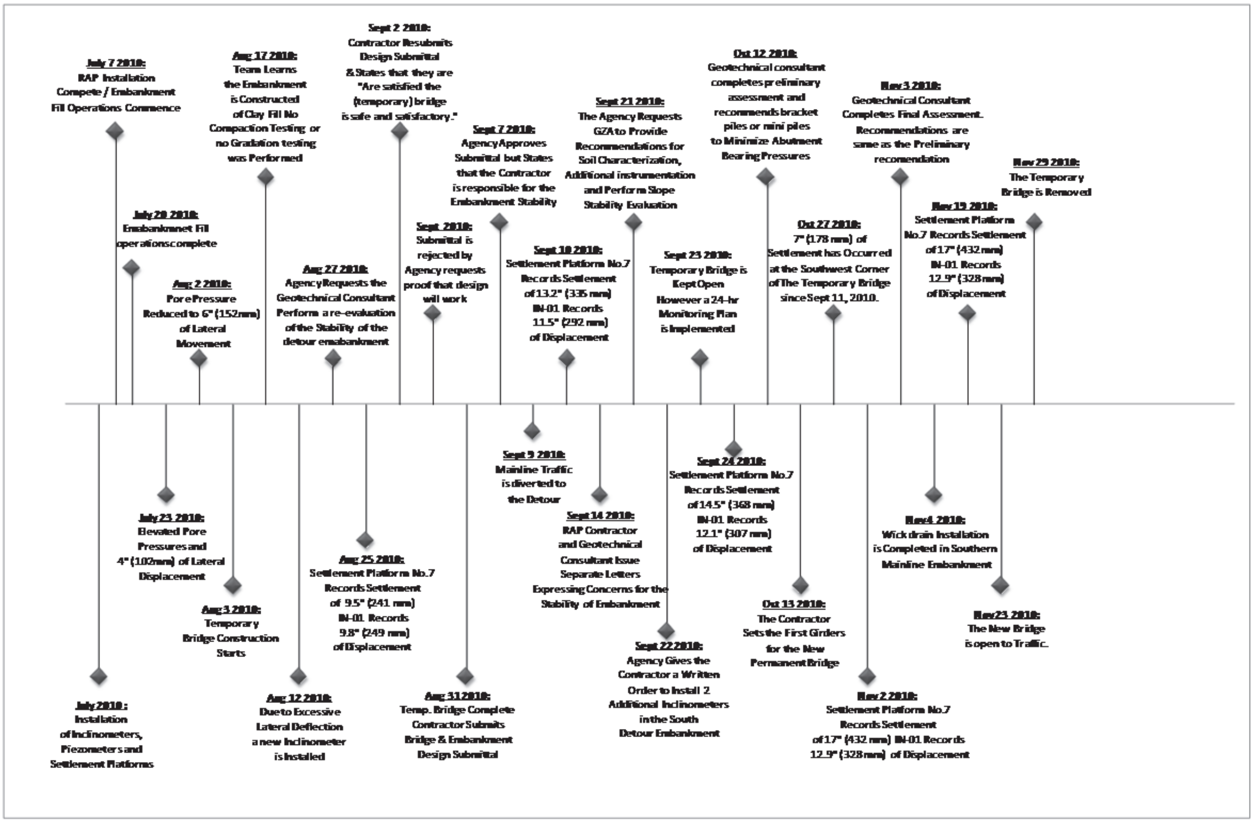


Table 2 – Construction Timeline



Bridge Construction Commences

Due to budgetary constraints and the remote location of the site, the geotechnical consultant was not retained to perform construction oversight of the project. Although the Agency did assign a resident engineer to oversee the project, a geotechnical engineer from the owner was only intermittently on site during construction.

At the start of construction, the RAP subcontractor developed the design submittal for the RAP ground support for the south embankment and abutment based on the limited subsurface information (boring logs) that were included in the contract documents and previous knowledge developed during the design phases of the project in discussions with the geotechnical consultant. During the review of the submittal, the geotechnical consultant noted the RAP design was not developed with the same soil properties outlined in the project geotechnical report. Noting that the Geotechnical Report was not included as part of the contract document package, a copy of the report was provided and the RAP contractor revised the ground support design using the recommended soil parameters and the revised submittal was accepted by the Agency and the geotechnical consultant.

As shown on the timeline in Table 2, the general contractor mobilized to the site and retained a third party geotechnical consultant as required to install piezometers and inclinometers at the locations shown in Figure 4.

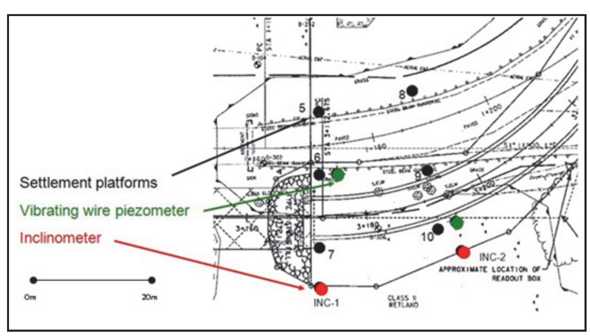


Figure 4 – Instrumentation Plan

Following the instrumentation installation, the RAP subcontractor mobilized to the site, installed the test RAP and set up the modulus test. Meanwhile the RAP installer continued to install RAPs at their own risk prior to the completion of the modulus test. The modulus test was conducted and the results confirmed the RAP design stiffness and installation procedures.

Embankment Construction

Immediately following the completion of RAPs, the general contractor began to place fill for the southern detour embankment (July 7, 2010) as seen in Figure 5.

Figure 5 – “Controlled” Placement of Clay Fill

The embankment fill was placed rapidly with limited field inspection and no compaction testing or laboratory testing. However, the geotechnical design consultant was not made aware of the fill operations until July 12, 2010, when the first instrumentation report was submitted indicating elevated pore pressures (approximately 10 ft (3 m) of water head). In addition, inclinometer data were not available at the time since INC-1 had not been replaced after being damaged during RAP installation. The first data obtained at inclinometer INC-1 were not available until July 23, 2010 and these data indicated a lateral displacement of approximately 4 in (102 mm) to the west at a depth of 16 ft (4.9 m) below ground surface. See Figure 6.

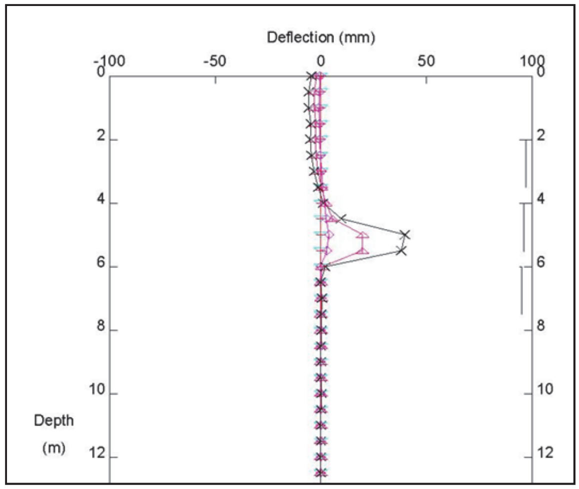


Figure 6 – INC-01 Deflection Results on 7/23/10

The project team immediately requested that fill operations be stopped until instrumentation readings stabilize. However, the embankment fill operations had already been completed for three days.

General Contractor Design Submittal

On August 3, 2010, the general contractor began construction of the temporary bridge without design approval from the Agency. As noted in the construction timeline, their design submittal was not transmitted to the Agency until August 31, 2011 after the temporary bridge had been completed. The initial design submittal was rejected on the basis that it did not meet Agency submittal requirements which indicate that the “Roadway approach embankments shall be constructed of acceptable fill material, compacted to adequately support design loading requirements.”

The Agency requested the general contractor to provide either compaction test results or other data to document that the fill material was placed adequately and could support the design loading requirements. The Agency also stated that in evaluating the ability of the fill embankment to carry the design loads, the stability of the underlying native material must be evaluated as well. Also, the general contractor was asked to demonstrate that there was an adequate factor of safety for the global stability of the fill and the underlying material under the anticipated loading conditions.

The general contractor resubmitted their temporary bridge design submittal but did not provide design basis or fill compaction documentation and simply indicated that the general contractor and contractor's engineer "are satisfied this (temporary) bridge is safe and satisfactory." The Agency approved the temporary bridge submittal, but emphasized that, because the embankment fill was undocumented, any issues with the stability of the approach embankment were the sole responsibility of the general contractor. Specifically, should there be a failure of the temporary embankment, any work associated with repairing that failure will be at the general contractor's expense. This work could include obtaining permits and permissions necessary to work outside of the defined construction limits in order to correct problems with the embankment.

Detour Opens

On September 9, 2010, the Rt. 125 mainline was closed and traffic was diverted onto the detour alignment and temporary bridge. However, instrumentation readings indicated that settlement and lateral displacement continue to occur. At this time, the geotechnical consultant and RAP contractor submitted letters to the Agency stating concerns about the stability of the detour alignment and concerns for traffic safety. The Agency decided to keep the detour open; however, the bridge and approach embankments would be monitored continuously for signs of accelerated displacements and potential catastrophic failure.

Embankment Reassessment

The Agency requested the general contractor to install two additional inclinometers at the top of the detour embankment slope to further evaluate the lateral displacement of the embankment. In addition, the Agency requested that the geotechnical consultant re-evaluate the overall stability of the approach embankment based on the instrumentation data and actual site conditions.

The geotechnical consultant performed a slope stability analysis to determine the root cause of the embankment movement and to recommend mitigation measures. During the evaluation, two major discrepancies between the original design and the actual embankment construction were discovered. Consistent with the original design and the RAP submittal developed by the specialty subcontractor, the approach embankment was to be constructed with compacted granular fill. However, with the exception of an initial lift of sand fill, the contractor had constructed the embankment with loosely compacted clay fill (see Figure 7).

Figure 7 – The Clay Fill was only compacted during placement with a Dozer.

The second major discrepancy was the assumption that the temporary bridge south abutment would be pile supported. However, the general contractor constructed a 3-span temporary bridge that incorporated two pile-supported intermediate piers and abutments supported on spread footing foundations bearing at the top of the approach embankments as shown in Figure 8. This significant discrepancy was not realized until the contractor had submitted the bridge design *after* the bridge had been constructed.

Figure 8 – Abutment Bearing at Top of Embankment.

The geotechnical consultant performed a complete stability evaluation of the approach embankment utilizing in-situ and laboratory testing information from samples obtained during the installation of the two additional inclinometers at the top of the south detour embankment. See Figure 9.

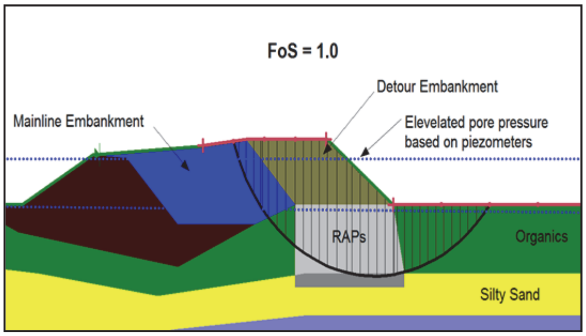


Figure 9 – Stability Results Based on Elevated Pore Pressures

The results of the evaluation indicated the following:

- The area showing the most movement is the southern abutment side slope. This was consistent with instrumentation obtained data to date.
- The initial lateral movement observed in INC-1 may be attributed to increased pore pressure developed during RAP installation followed by the immediate, rapid embankment filling.
- The lateral movement was then exacerbated by the subsequent application of unanticipated abutment loads from the detour bridge.

To increase the embankment's global stability factor and limit further lateral deflection, the geotechnical consultant recommended that the bridge abutment pressures be reduced. To achieve this, the general contractor would have to underpin the abutment foundation with micropiles or some other deep foundation system. A counter berm was also recommended as another mitigation alternative. However, due to wetland encroachment restrictions this was not a feasible measure. The contractor chose to accelerate permanent bridge construction rather than implement mitigation measures.

Permanent Bridge

Although the general contractor's original plan was to complete the new bridge prior to winter shutdown, it was not going to be opened to traffic until spring when the approaches and paving would be complete. As a result of the concerns for public safety, the Agency had the general contractor accelerate the completion of the approaches to the bridge and place temporary pavement on the bridge deck so that the detour did not need to be maintained over the winter months. The detour embankment was monitored on a full time basis for safety reasons until the general contractor was able to open the permanent bridge. November 23, 2010, the permanent bridge was opened to traffic. November 28, 2010, the temporary bridge and detour embankments were removed. The total settlement for the south detour abutment area was 17.7 in (450 mm). The total lateral displacement in the same area was approximately 13 in (330 mm). See Figure 10.

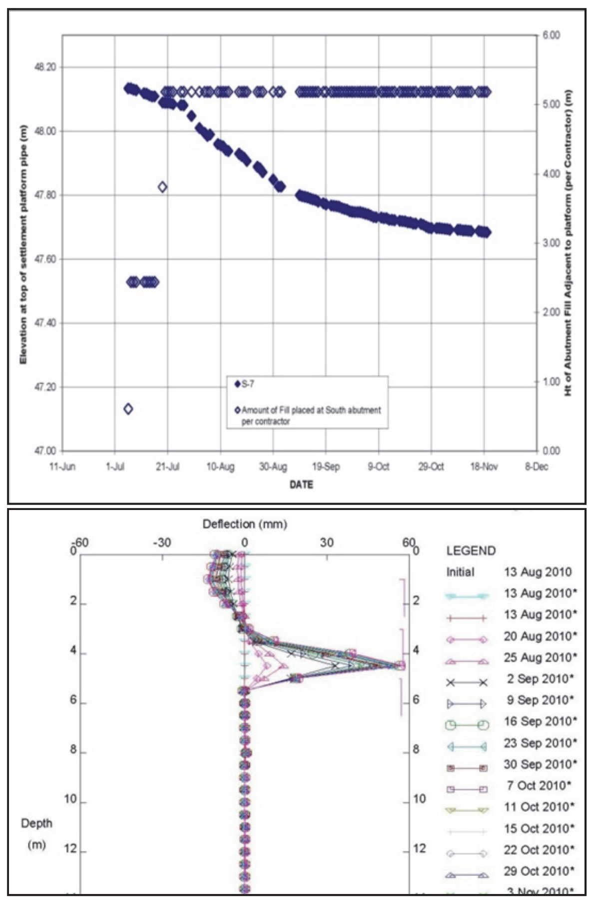


Figure 10 – Settlement and Inclinometer (Partial Plot) Results

Summary / Lessons Learned

The problems encountered during the construction of the detour bridge and approach embankment demonstrated how the lack of communication and coordination can derail any project despite the initial good intentions. Disconnect between design assumptions and actual construction caused a potential public safety issue that may have resulted in catastrophic disaster. For that reason, it is important to review and recognize the lessons learned to prevent a similar situation from happening again.

Lesson 1 – Differences between design assumptions from those in the contract documents.

As discussed, the original design was based on assumptions that the embankment was to be constructed of compacted granular fill and the bridge abutment was to be supported on piles. The Agency's standard specifications for the project indicated that the contractor can use any material for temporary fill embankments. However, the contractor needs to demonstrate in a design submittal that the embankments will be stable. Despite repeated requests for coordinated embankment and temporary bridge design submittals, the general contractor was allowed to construct the bridge and embankment "at risk" with the assumption the bridge design submittal would be approved. The bridge design submittal was sent to the Agency *after* the detour bridge and embankment were completed and the submittal did not include design assumptions or calculations but stated that "the contractor and its engineer feel the bridge and embankment were stable". At this point, the Agency should have rejected the submittal as incomplete. However, in an effort to keep the project moving, the bridge design submittal was approved on the basis that the contractor would be responsible if the bridge or embankment failed.

The lesson learned is the design submittal process needs to be formalized, coordinated, and enforced. The embankment and bridge construction should have been halted until a complete, coordinated design was approved by the Agency and geotechnical consultant.

Lesson 2 – Standard Specifications for temporary bridge construction

The Agency specifications for temporary bridge and embankment construction are very general and vague. It appears the specification was developed under the assumption that the temporary bridge and embankment would not be used for a long duration. Therefore, the contractor would have the opportunity to select the most convenient and cost-effective materials for the temporary bridge and approach embankments. This may result in a cost savings to the Agency on most projects that are constructed on relatively competent soils. However, if the site has soft, compressible soils like this project or if the temporary bridge is to remain in service for an extended period of time, the bridge design and approach requirements should be carefully detailed in the contract documents. The project team decided to follow standard format and bid the temporary bridge in accordance with the Agency's standard specification which in hindsight was a mistake. The standard specification was also quite vague regarding requirement for a design submittal. The Section simply states that the contractor shall demonstrate that the temporary embankment and bridge will be stable.

Lesson 3 – Failure of the RAP contractor to discuss the type of fill to be used for the fill embankment.

The RAP subcontractor was retained by the general contractor to design and install the RAP ground support system. Although the RAP design submittal indicated embankment fill was to be placed above the reinforced ground in accordance with project specifications immediately after the RAPs were installed, the RAP subcontractor left the site and was unable to observe the contractor's fill placement operations. More coordination and discussion between the general contractor and the RAP subcontractor may have brought to light the potential issues of fill material that was inconsistent with the assumptions upon which the RAP embankment ground support submittal was developed.

Lesson 4 – Lack of fill placement oversight and documentation

There was limited oversight and little documentation of fill placement for the temporary bridge embankment. The Agency decided not to have the geotechnical consultant perform construction oversight due to budget constraints. The Agency also did not assign a geotechnical engineer from the department to observe and document the project due to staffing issues. If a geotechnical engineer familiar with the basis of the design saw the type of material and the method of compaction used to construct the embankment, or noted the construction of a spread footing foundation at abutments that were to be pile supported, the process would have been stopped immediately before additional problems developed.

Lesson 5 – Instrumentation data were not distributed in a timely manner.

Initially, instrumentation data were not distributed to the geotechnical consultant until the fill embankment had been nearly completed. This was an issue since the general contractor began placing fill before pore pressures were allowed to dissipate following the completion of the RAPs. Ideally, fill placement would not have commenced until after pore pressure returned to preconstruction levels. Also, inclinometer data indicating large lateral displacements were not provided until after the embankment was constructed. Ideally, instrumentation data should have been obtained and transmitted to the project team daily during fill placement operations. The general contractor should not have been allowed to start fill placement until the project team had a chance to review instrumentation data.

Conclusion

There is no clear reason for the poor performance of this carefully designed and well engineered project. However, the process inherent in the Design-Bid-Build system used to procure the majority of public sector construction significantly contributed to the problems experienced by this project. Budget constraints and competing project priorities dictated the 9-year-long period from design through construction resulting in numerous starts/stops in the design work and unnecessary involvement of personnel that were not familiar with the overall project. Then, following a long delay, available funding required the project to be advertised for bid on short notice providing little time to assemble bid documents and ensure a thorough, complete, and coordinated review of the bid package prior to advertisement. Further budget constraints prevented the full-time involvement of qualified geotechnical professionals, thoroughly knowledgeable with the design of this clearly non-routine project from being assigned to observe and document field construction.

From the start of construction, the initial design of the ground support system was submitted by the specialty geotechnical construction subcontractor, reviewed, and subsequently approved after which time ground support construction commenced. However, other design submittals that were the responsibility of the general contractor were not developed, coordinated with the subcontractor's ground support design submittal, and transmitted in a timely manner. Yet work was permitted to continue under the pretense that the general contractor was completing work at his own risk and remained responsible for all aspects of the work. Although this may seem like a convenient means for the owner to keep the risk associated with the work with the contractor, the fact that work was completed under the observation of the owner's resident engineer that was not consistent with an approved submittal may have implicated the owner with some responsibility.

However, clearly one of the most apparent shortfalls in the project was the lack of clear, consistent communication between the members of the design and construction team. The scope of the ground support subcontractor was strictly limited to design and construction of the ground support system after which time it was assumed that the general contractor was responsible for completing the remainder of the work in accordance with the project specifications, requirements, and approved submittals. The instrumentation specialist retained by the general contractor was strictly responsible for installing and monitoring instrumentation designed by the owner to document project performance as required as part of the project's FHWA funding as a Category II Experimental Feature. Weekly submittal of instrumentation reports was required by the contract documents. Unfortunately, these data was not transmitted to the geotechnical consultant for timely review in conjunction with ongoing construction activities until most to the temporary embankment was constructed. Each of these missed communication links prevented timely and appropriate follow-up that may have prevented the development of the problems and performance described herein.

Still, in spite of all of these shortcomings, the overall response of the design/construction team prevented a potential catastrophic failure from occurring and construction was completed with limited delays and additional expense. However, these lessons should be recognized by other design and construction professionals so that proactive measures are taken to prevent similar problems from occurring on future projects.